Internal Waves Over the New England Shelf

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LONG-TERM GOALS

Our long-term goal is to better understand processes controlling the horizontal and vertical distribution of internal wave energy over the continental shelf. Emphasis will be placed on the near-inertial band. Both the initial response to impulsive forcing and the overall distribution of near-inertial energy will be considered.

OBJECTIVES

We will investigate several aspects of the internal wave field over the New England Shelf, considered to be representative of a general class of broad, gently-sloping shelves. Specifically, we intend to characterize the horizontal and vertical structure of the internal wave field over the shelf and examine how coastal geometry, stratification, and background flow act to modify the near-inertial response to impulsive wind forcing.

APPROACH

The project can be broken down into three distinct, but related, areas: data analysis, analytical modeling, and numerical modeling. Data from the Nantucket Shoals Flux Experiment (NSFE) and the combined Coastal Mixing and Optics (CMO) and Shelf Break PRIMER experiments will be investigated using standard time series analysis techniques. Characteristics of the internal wave field will be documented and the near-inertial signal will be isolated. Due to differences in instrumentation and array geometry, the NSFE data are best suited to examine horizontal variability while the CMO/PRIMER observations will be used to study both vertical and horizontal structure. Surface forcing fields will be examined to identify individual forcing events that evoke strong near-inertial responses. Analytical models based on the two-layer formulations of Pettigrew (1980) and Millot and Crepon (1981) will be used as a guide to interpreting the observations. If the observed stratification warrants the additional complexity, a continuously stratified model (Kundu et. al., 1983) will be employed. A two-dimensional, nonlinear numerical model will be used to investigate the mechanisms controlling the cross-shelf structure of near-inertial energy. This work will follow that of Federiuk and Allan (1996) and Chen and Xie (1997). The intent is to incorporate surface forcing, cross-shelf topography, and stratification which is more realistic than that of the analytical models.

WORK COMPLETED

Progress has been made on the data analysis and analytical modeling aspects of the project. The complete NSFE data set has been obtained, and Acoustic Doppler Current Profiler (ADCP) records from Shelfbreak PRIMER have been combined with current meter data from the CMO moored array. The near-inertial signal has been extracted from both NSFE and CMO/PRIMER data sets. Surface forcing events warranting further study have been identified for NSFE following Wood and Chapman (1989) and for CMO/PRIMER using the buoy meteorology and the regional model results described by Baumgartner and Anderson (1999). A hierarchy of two-layer analytical models (of increasing complexity) has been developed. The impulsive forcing (delta function) case described by Pettigrew (1980) was re-derived and extended to include both propagating step function forcing (representing the leading edge of a front) and propagating pulse forcing (representing the leading and trailing edges of a storm system).

RESULTS

The near-inertial signals extracted from both NSFE and CMO/PRIMER show responses to surface forcing which can be approximated as a two-layer flow. Comparing near-inertial currents near the surface with those near the bottom highlights this quasi two-layer response. There is a tendency for oscillations in the upper and lower layers to be approximately out of phase, although many events show phase variability. Four typical cases can be distinguished based on the relative phase and strength of currents in each layer (Figure 1). As anticipated, much of the variability is related to changes in the background stratification. Heating in spring and summer results in a thin surface layer and enhanced upper layer currents (Figure 1a). In fall and winter the pycnocline is eroded by growing surface and bottom mixed layers, creating nearly equal layer thicknesses and current amplitudes (Figure 1b). If mixing is strong enough, the water column may be well mixed, resulting in currents which are nearly in-phase and comparable in amplitude (Figure 1c). At other times near-bottom intrusions of slope water can create a thin lower layer, resulting in enhanced lower layer currents (Figure 1d).

Simple extensions of the original two-dimensional, two-layer model (Pettigrew, 1980; Millot and Crepon, 1981) introduce considerable variability in the response. Following the original configuration, forcing the model with spatially uniform, impulse (delta function) offshore wind generates a response where upper and lower layer velocities are 180° out of phase (Figure 2). This two-layer structure is actually a superposition of upper-layer inertial oscillations driven directly by the wind and a barotropic response that propagates rapidly outward from the coast. A baroclinic response propagates away from the boundary more slowly and, at longer time scales, acts to modulate the response in both layers. The phase relationship between upper and lower layer currents is a characteristic of the two-layer response to spatially uniform impulse forcing, and is similar to several of the events identified in the observations.

To examine the effects of forcing by atmospheric fronts moving in the offshore direction, we derived solutions for forcing by a propagating step function and for propagating pulse forcing. Now, in addition to barotropic and baroclinic waves that propagate outward from the coast, the response includes effects associated with the leading and trailing edges of the atmospheric system. In both cases,

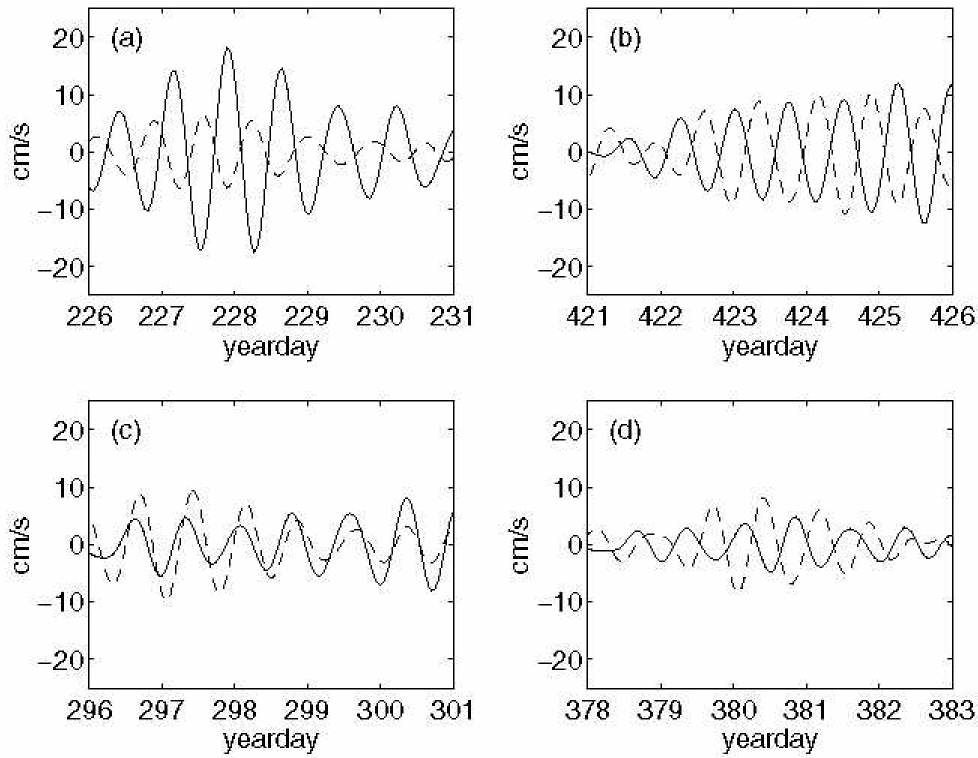

Figure 1. Observed inertial-band velocity response from instruments near the surface (solid lines) and near the bottom (dashed lines) are shown for differing background stratifications. (a) CMO/PRIMER data in summer showing enhanced surface currents and variable phase through the event. (b) CMO/PRIMER data in winter showing nearly equal amplitude currents with phase near 180 degrees. (c) NSFE data in fall showing approximately in-phase response. (d) CMO/PRIMER data in winter showing enhanced bottom currents and variable phase.

the response is sensitive to the speed of the front relative to the barotropic wave speed. As might be expected, the duration of the pulse can also play an important role in governing the response. Upper and lower layer currents are no longer phase locked, and their phase relation evolves over time. We have only just started exploring the parameter spaces of these two models, but offer an example below. In this case, upper and lower layers are of equal thickness, the inertial period is 18.2 hours and we force with a translating pulse of offshore wind lasting 6 hours. For a front translating much faster than the barotropic wave speed, the upper and lower layers begin out of phase, but drift back into phase over the course of several inertial periods (Figure 3). Interestingly, lower layer amplitudes are larger than upper layer amplitudes. When the atmospheric front translates more slowly than the barotropic wave speed, both layers respond in phase and with similar amplitude. In the limit of very rapidly translating fronts, upper and lower layers respond with equal amplitudes, 180° out of phase. The phase and amplitude variations introduced by translating forcing offer greater latitude to describe, and hopefully understand, variability in the observed response. We are currently working to determine how the various elements of the model response react to changes in forcing. For example, if the barotropic response moves offshore faster than the atmospheric front, how will it modify the generation of directly wind forced inertial motions in the upper layer? Will the presence of barotropic inertial oscillations damp the generation of upper layer inertial motions?

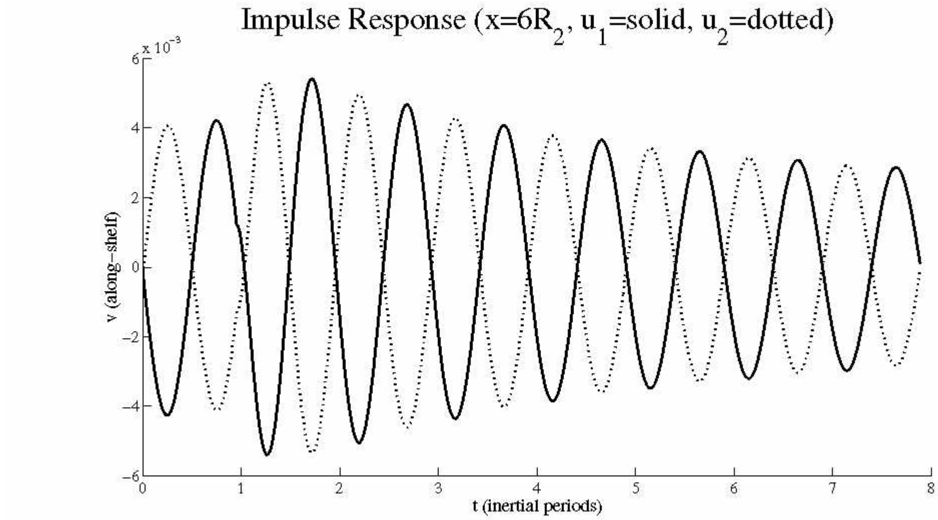

Figure 2. Along-shelf velocity for the upper (solid) and lower (dotted) layers of the two-layer model forced by a spatially uniform impulse wind. Layer depths are of equal thickness. Results are shown as a function of time at a location 6 internal Rossby radii from the coastal boundary. The barotropic response arrives almost instantaneously, while the baroclinic response requires nearly one inertial period to reach this location from the coastal boundary.

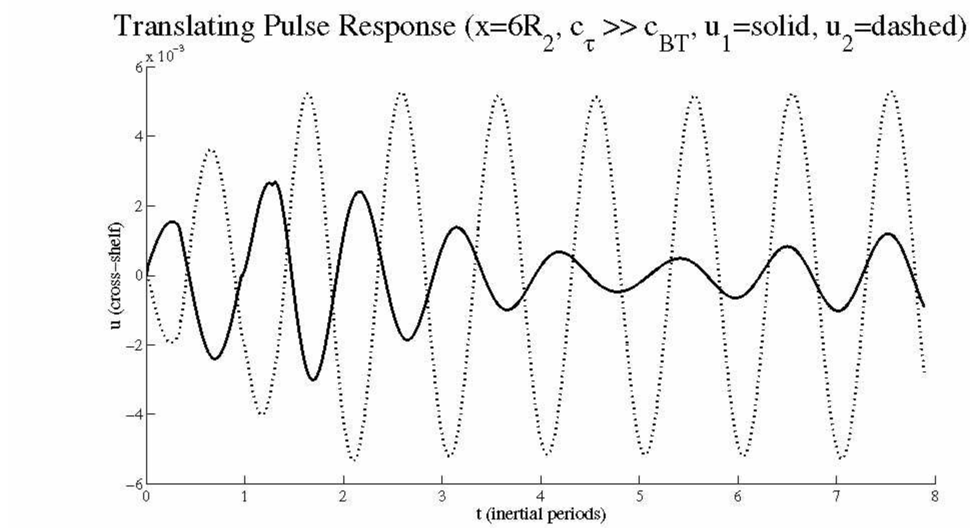

Figure 3. Cross-shelf velocity plotted an in Figure 2. Here, a translating pulse of offshore wind forces the model. As before, layer depths are of equal thickness and results are shown at a location 6 internal Rossby radii from the coastal boundary. Pulse duration is approximately a third of an inertial period and it translates in the offshore direction at four times the barotropic wave speed.

IMPACT/APPLICATIONS

By extending both analytical and numerical work done by previous investigators, we hope to elucidate the principal processes which control the near-inertial response on broad, shallow shelves. Through comparison with observations the ability of simple two-layer models and more complex numerical models to reproduce the observed response will be evaluated.

TRANSITIONS

None.

RELATED PROJECTS

We are using archived data from NSFE (supported by the National Marine Fisheries Service, the U.S. Geological Survey, and the National Science Foundation). Our participation in the CMO moored array project (funded by the Office of Naval Research) provided a high-quality, high-resolution continental shelf data set, which was further enhanced through cooperation with investigators from the Shelfbreak PRIMER experiment (also funded by ONR).

We are sharing data and results with M. Levine and T. Boyd at Oregon State University (OSU) who are funded by ONR to investigate the coastal internal wave field. We will concentrate on characterizing the near-inertial band (cross-shelf structure, vertical structure and response to impulsive forcing) over a broad shelf, whereas the OSU group will consider the internal wave field as a whole, focussing on the shape and level of the energy spectrum on both narrow and broad shelves.

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